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WORKING PAPER

EYE/SENSOR PROTECTION BY AN OPTICAL FUSE MIRROR AT A FOCAL PLANE

FEASIBILITY ASSESSMENT

August 7, 1989

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BACKGROUND

The protection of eyes and electro-optic sensing devices from direct exposure to laser radiation has become an important and difficult challenge to the scientific and engineering community. Acceptable systems must protect against a wide range of wavelengths and intensities, and must be effective against both CW and pulsed radiation. Almost certainly, no one technique will be effective against both CW and pulsed lasers and at all possile wavelenghts and thus a multicomponent system is envisioned.

The optical gain of the human eye is 10^5 to 10^6 depending on wavelength and pupil size (i.e. dark adapted or not). The damage threshold for the human retina is of the order of 2 J/cm^2 so an incident radiation flux of 2 microjoules/cm^2 at the front surface of the eyeball (cornea) must be hardened against. Most materials have damage thresholds in the range of 0.5 to 3 J/cm^2 of absorbed laser energy, not at all surprisingly similar to the damage threshold of the retina. To protect the eye without use of an optical device with a focal plane used to intensify the light at an optical switch, fuse or limiter, or without a powered activation system of some kind may prove impossible. Such a system without a focal plane would require an optical switch is activated at energy densities of the order of a microjoule and operation in the nanosecond time frame. An electrically driven (active) system may provide greater sensitivity and thus a lower switching threshold than a passive device. Even so, a microjoule threshold is indeed a challenge to the technical community.

OPTICAL FUSE CONCEPT

One possible approach to protecting eyes and sensors is to use a device having a focal plane with an optical switch or optical fuse at or near the focus. The fuse could be manually reset to a fresh undamaged section following its failure. A variety of optical fuse concepts using a focal plane may be envisioned. One such system employs a thin metal reflector at the focal plane which reflects the image to another optic which reimages the light on the eye, (see figure 1). The thin reflector is designed to ablate at a threshold below that which is damaging to the eye, dumping the laser energy behind the destroyed mirror. When the threat has subsided, the optical fuse/mirror may be manually repositioned to a fresh reflective surface.

FEASIBILITY ASSESSENT

Optical Fuse Threshold

In order for a mirror to serve as a suitable optical fuse for eye protection, it must fail at energy densities lower than the damage threshold of the retina. The reflective layer must absorb sufficient energy to render the mirror transparent, highly absorptive, or highly scattering. The higher the ambient absorptivity of the proposed mirror/optical fuse, the lower its threshold for protection, but also the lower the level of ambient light reaching the eye. A 10-20% ambient absorptivity would more than likely be acceptible for device application, and possibile even 30%. If the threshold for retinal eye damage were taken to be $2uJ/cm^2$ at the pupil and the optical gain of the protective device were 10^5 with a 10% mirror absorptivity, then a suitable mirror/optical fuse at the focal plane would require a failure threshold of 0.02 J/cm^2 of absorbed energy. If a device with an optical gain of 10^6 were attainable in an acceptible size and configuration for field use, this threshold could be increased to $0.2J/cm^2$ absorbed at the

focal plane. Another factor of two on three could be gained by increasing the ambient light absorption of the mirror from 10% to 20% or 30%. The feasibility of such a device is limited by the practicality of optical configurations and the ability to design a mirror/optical fuse which fails at absorbed energy densities of the order of 0.02 to 0.4 J/cm^2.

Work involving the laser ablation of thin reflective layers of aluminum on Kapton was conducted by Jack McKay in the late 1970's, then at the Naval Research Laboratory and currently at Physical Sciences, Inc., Alexandira, VA. His results are in general agreement with these.

Failure Mode

A mirror/optical fuse may fail by removing the reflective layer (front surface or back surface). The reflective surface may be vaporized or in certain configurations, melted or roughened which requires considerably less absorbed energy than vaporization. For a first approximation, consider a simple thin aluminum reflective layer. To melt the layer requires energy to heat it to its melting point plus the enthalpy of fusion (402 J/gram). To volatilize it requires an additional energy input to raise its temperature to the vaporization point plus the enthalpy of vaporization (10500 J/gram). To a first approximation, energy lost to radial thermal conductivity in the reflective layer and radiactive and convective cooling is negligible. The irradiated spot on the mirror/fuse at the focal plane is less than 0.01 cm in diameter. A general guideline for considering the importance of radial thermal conductivity in a laser irradiated target is that it is negligible if 4kt is less than the diameter of the irradiated spot, where k is the thermal conductivity (ca. 0.6 for aluminum) and t is the laser pulse duration. Thus for spots less than 0.01 cm in diameter with pulses shorter than a microsecond, radial thermal conductivity in a thin reflective layer of aluminum may be neglected as a significant mechanism for energy loss.

Tabulated in Table I is the results of calculating the threshold irradiance incident (not absorbed) at a focal plane reflector required to melt or vaporize a mirror layer of aluminum which absorbs 10% of the incident radiation. The absorptivity of the metal layer could be adjusted by incorporating controlled impurities (e.g. carbon) by vapor deposition or by other techniques. In a real system, the absorbtivity may be adjusted to any acceptable value and the reflective layer is not limited to aluminum, but perhaps some alloy with low enthalpies and temperatures of fusion and/or vaporization. As can be noted in Tale I, thresholds for melting and vaporization each increase linearly with thickness, while there is a factor of 5.7 increase between the energy required to melt and the energy required to vaporize aluminum.

The thinest layer of aluminum which makes a good mirror is about 70-100 nm. If a thin reflective layer supported on a substrate were melted, it may not be removed rapidly enough to protect the eye, therefore an effective system may require total vaporization of the film. On the other hand, if the reflective layer were a free standing film (in this case aluminum), melting would be sufficient to produce a hole in the reflector and thus serve as an optical fuse. Following failure, the mirror/fuse could be repositioned to a fresh location. The thin free standing portion of the mirror/fuse need only be slightly larger than the size of the focused image, realistically, about 10^{-2} to 10^{-3} cm in diameter. Outside the focal point the film need not be free standing but may be supported on a suitale sustance. One could envision a mirror/fuse system, located at the focal plane of an optical system, consisting of a repositionable thin metal reflector (with customized absorbance), supported by a substststrate (glass, plastic, etc.) where several areas of the substrate (about ca.> 10^{-3} cm diameter) have been etched away leaving a free standing reflective film. The spots of free standing reflective films are located exactly at the focus of the optical system. The mirror may be manually repositioned following fuse failure to a new spot.

Obviously, a free standing film would have to be thicker than a reflective layer on a substrate in order to support itself. From the date in Table I, for aluminum, the trade off in thickness versus optical fuse failure threshold is a factor of about 5.7 in thickness (i.e. difference between melting and vaporizing). The question is, to compete with vaporization of a 100 nm thick (or less) reflective layer on a substarate, can a free standing reflective film, only ca. 10^{-3} cm in diameter, be fabricated and mechanically stable with a thickness of only 570 nm or less and still by optically flat?

Improvements on the Concept

Several variables may be adjusted in order to reduce the failure threshold of the proposed mirror/fuse. Calculations in Table 1 are for aluminum with a normal absorption of 10%, adjusted by controlled spoiling (contamination) of the reflective surface. This could be increased a factor of 2 or more and still meet minimum acceptible optical requirements for certain field applications. The mirror/optical fuse is certainly not limited to aluminum. Reflective materials are available with much lower melting points and heats of fusion and vaporization than aluminum. The reflective layer could be sealed in a small vacuum or gas filled cell, thus allowing use of materials which otherwise may oxidize. Amalgams or alloys may also be employed.

Another way to lower the threshold for fuse failure is to use a substrate, rather than a free film, and place between the substrate and the thin reflective layer a thin layer of material (probably a polymer or certain inorganic crystal systems) having a very low thermal stability, which, upon thermal shock produced by partial absorption of laser energy, produces rapid decomposition thus "blowing off" the reflective layer. This system could be designed to be irradiated either through a transparent substrate and the partially absorbing decomposing layer which lies between the substrate and the mirror layer (back surface mirror system),

or the system could be designed as a front surface mirror, with partial absorption by the reflector, resulting in heat transfer (thermal shock) to the decomposing layer below. Numerous polymer coatings can be envisioned with low thermal stabilities as well as by a variety of inorganic crystals. Inorganic crystals exhibiting rapid decompositon with low and distinct temperature or thermal shock thresholds include the monovalent metal azides, fulminates, and ammonium pennanganates and halates. The area coated with these less stale materials may be limited to ca. 10^{-3} cm spots at the focal point. Such a thermochemically assisted system may considerably reduce the response time and energy threshold for fuse failure below that for a free standing metal reflector.

The reflective system need not be limited to a metal. Numerous polymers exist which themselves may be sufficiently metal like to be suitable reflectors and which may have intrinsically low thresholds for thermal damage.

CONCLUSION

The system described above appear to be borderline feasable for the protection of eyes from pulsed laser radiation if an optical system with a focal plane havaing a gain of ca. 10^5 or greater were acceptable. A variety of techniques to lower protection thresholds are mentioned above, but more detailed analysis is required. The proposed concept using a rapidly decomposing polymer or inorganic crystal coating supporting the reflective mirror layer on a substrate should be investigated further with specific materials and their properties included in the analysis. This design may be worthy of a bread-board testing to experimentally determine thresholds.

ADDENDUM

Since the writing of this brief paper, I have read (thanks to Ed Sharp of the Army Night Vision Laboratory) a paper by Sztanky, McGuire, Wellmon and Errett published in 1974 by the Harry Diamond Laboratories, Adelphi, MD which proposed a mirror/fuse system similar to the one discussed above. Their findings are similar to those presented here but were limited to a front surface thin reflective layer on a black plastic substrate. The idea of a free standing reflective film or using a substrate thermochemically enhanced ablation mechanism was not discussed.

REFLECTIVE-FILM OPTICAL-FUSE FOR EYE AND SENSOR PROTECTION

REFLECTIVE LAYER	aluminum
SUPPORT SUBSTRATE	none - free film
ASSUMPTIONS	no thermal conductivity, radially or in depth
	sq rt of 4at less than focused spot size
	for optical gains 10 to 5 or 6 with 1 inch
	lens and pulse widths less tha 50 nsec or so
	reflectivity "spoiled" to give desired value

FRACTION RADIATION ABSORBED	0.1 (ie 1 - fraction reflected)
DENSITY REFL LAYER gm/cc	2.7
MELTING TEMP DEG C	660
VAPORIZATION TEMP DEG C	2327
AMBIENT TEMP DEG C	25
HEAT CAPACITY SOLID j/gm-C	0.901
HEAT CAPACITY MELT j/gm-C	1.08
HEAT OF FUSION j/g	402
HEAT OF VAPORIZATION j/g	10500
OPTICAL GAIN OF DEVICE	1.00E+05

If film absorption were raised (reflectivity lowered) Threshold would be lowered

If optical gain of system were raised, threshold for fuse would be lower

THRESHOLD j/sq cm	THICKNESS nm	THREAT FLUENCE j/sq cm	THREAT FLUENCE microjoule/sqcm	HEAT TO MP j/sq cm	MELTING j/sq cm	HEAT TO BP j/sq cm	VAPORIZE j/sq cm	TOTAL TO VAPORIZE j/sq cm
0.0827	50	8.27E-07	0.8267	0.0772	0.0054	0.2430	0.1418	0.4675
0.1157	70	1.16E-06	1.1573	0.1081	0.0076	0.3403	0.1985	0.6544
0.1488	90	1.49E-06	1.4880	0.1390	0.0098	0.4375	0.2552	0.8414
0.1653	100	1.65E-06	1.6533	0.1545	0.0109	0.4861	0.2835	0.9349
0.2480	150	2.48E-06	2.4800	0.2317	0.0163	0.7291	0.4253	1.4024
0.2811	170	2.81E-06	2.8106	0.2626	0.0185	0.8264	0.4820	1.5894
0.3307	200	3.31E-06	3.3066	0.3090	0.0217	0.9722	0.5670	1.8699
0.4960	300	4.96E-06	4.9599	0.4634	0.0326	1.4583	0.8505	2.8048
0.8267	500	8.27E-06	8.2665	0.7724	0.0543	2.4305	1.4175	4.6746
1.1573	700	1.16E-05	11.5731	1.0813	0.0760	3.4027	1.9845	6.5445
1.3226	800	1.32E-05	13.2264	1.2358	[illegible]	[illegible]	2.2680	7.4794
1.6533	1000	1.65E-05	16.5330	1.5448	0.1085	4.8610	2.8350	9.3493
8.2665	5000	8.27E-05	82.6652	7.7238	0.5427	24.3045	14.1750	46.7464
16.5330	10000	1.65E-04	165.3305	15.4476	1.0854	48.6097	28.3500	93.4926
24.7996	15000	2.48E-04	247.9957	23.1715	1.6281	72.9146	42.5250	140.2391
33.0661	20000	3.31E-04	330.6609	30.8953	2.1708	97.2194	56.7000	186.9855
41.3326	25000	4.13E-04	413.3261	38.6191	2.7135	121.5243	70.8750	233.7319
41.9939	25400	4.20E-04	419.9393	39.2370	2.7569	123.4687	72.0090	237.4716
0.0000		0.00E+00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000		0.00E+00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
0.0000		0.00E+00	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

↑ Threshold Incident Energy to melt a Free standing Film of Aluminum

Assumes 10% absorptive Film (90% reflective) optical gain of 10^5

↑ Threshold Incident Energy To Vaporize a Film of Aluminum